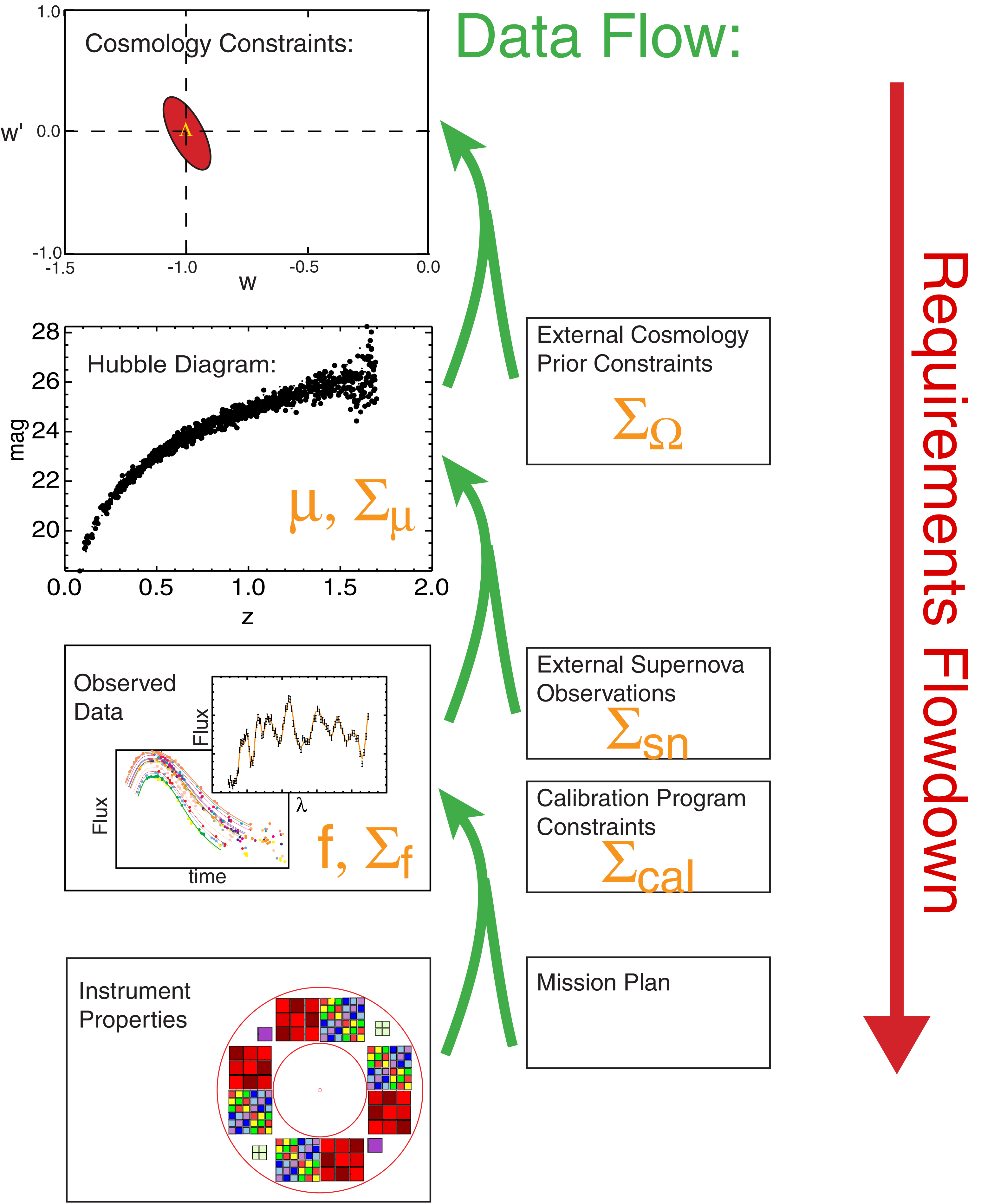
Simulations of SNAP Observations and Data Reduction

January 2003 AAS

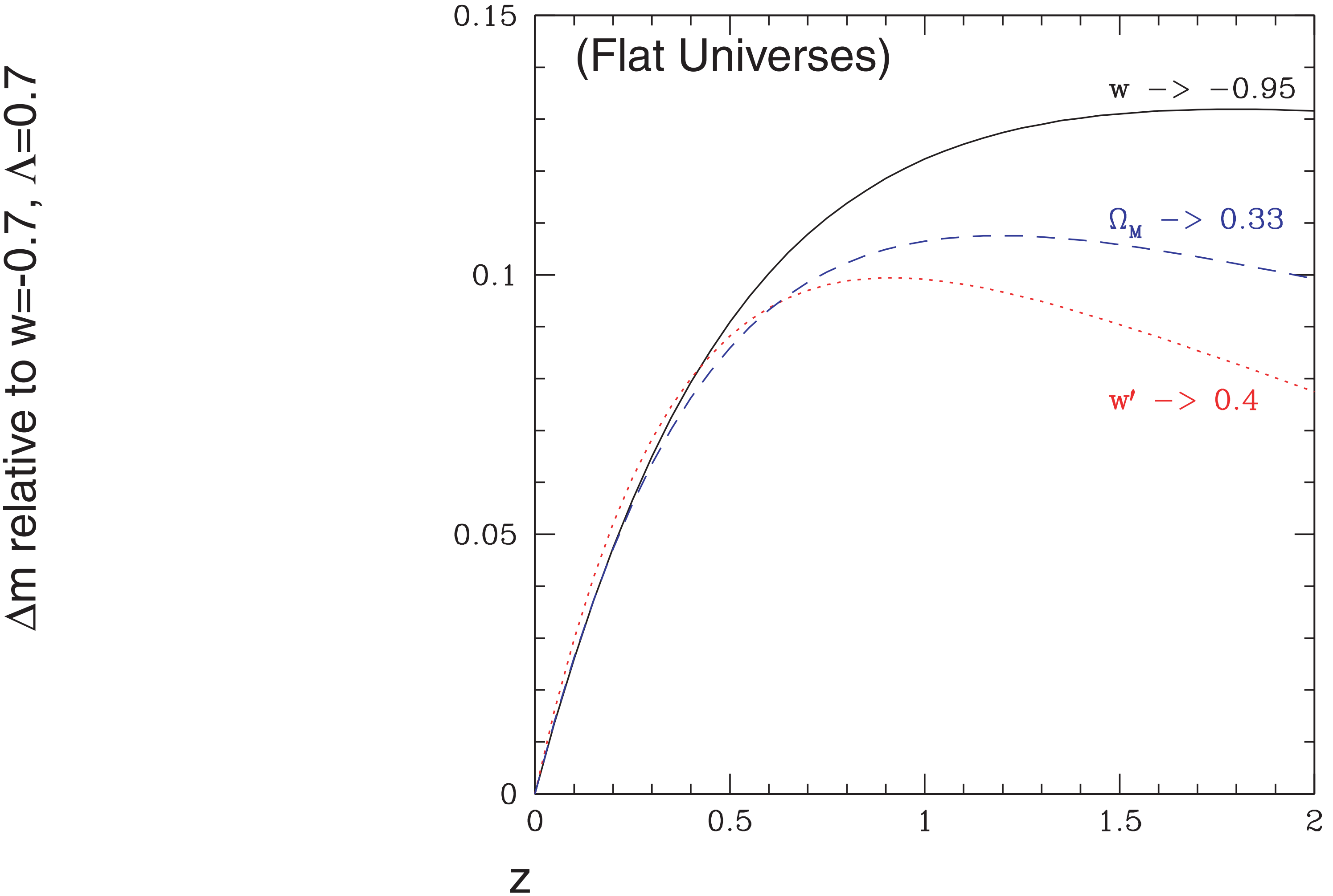
Presenter: Gary Bernstein
Representing: The SNAP Collaboration, particularly Alex Kim

- Overview of the SNAP supernova task
- Cosmology fitting: the easy final step
- Image & Spectroscopy reduction
- Modeling SN behavior & systematics: the hard part
- Predictions for SNAP & Ground-Based SN surveys
- SNAPSim: A tool for analysis of astronomical surveys



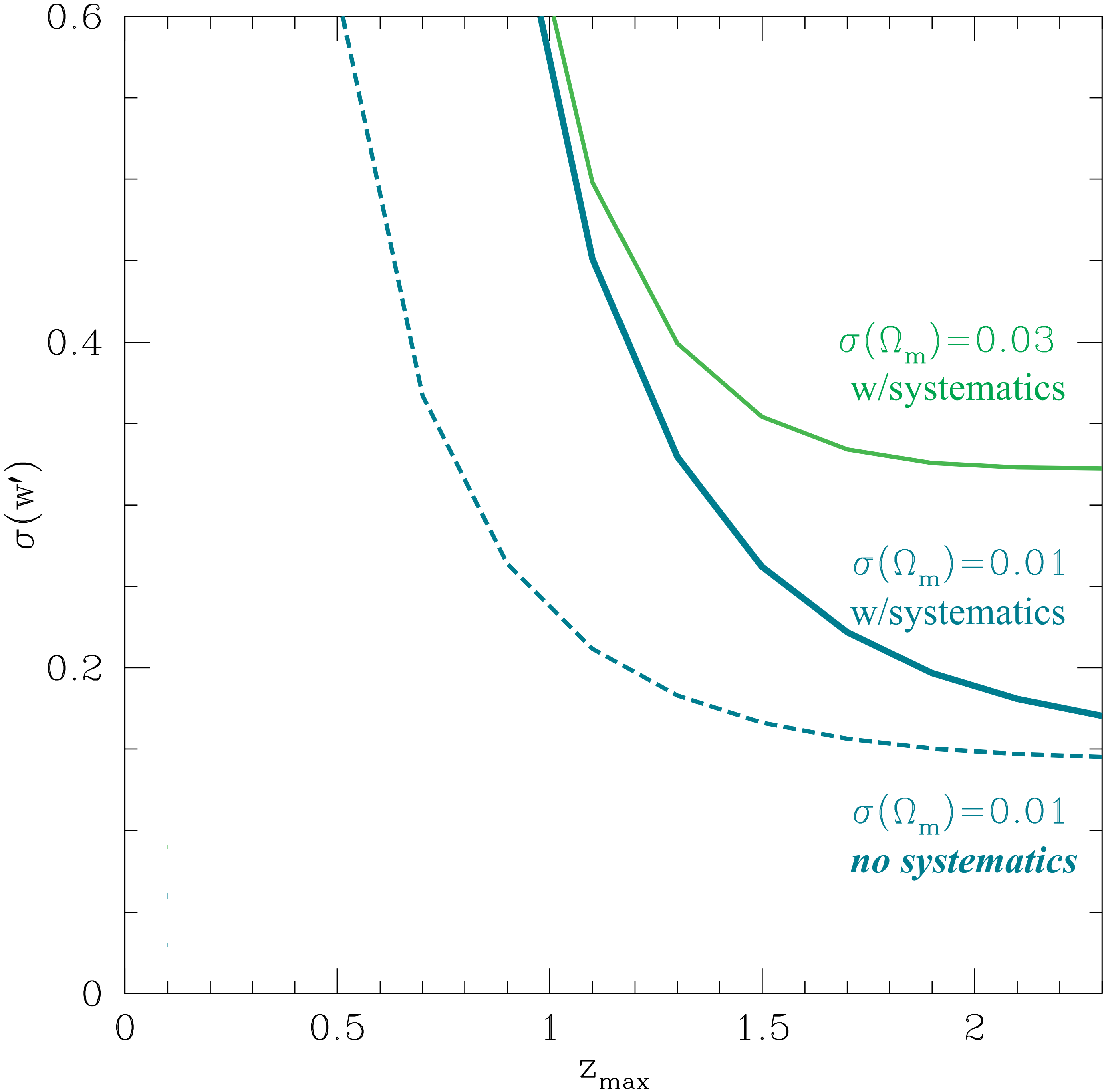
Data Flow:
Requirements Flowdown
Cosmology Constraints:
w'
w
1.0
0.0
-1.0
-1.5
-1.0
-0.5
0.0
Λ
Hubble Diagram:
mag
z
28
26
24
22
20
0.0
0.5
1.0
1.5
2.0
μ, Σ_μ
Observed Data
Flux
λ
Flux
time
f, Σ_f
Instrument Properties
External Cosmology Prior Constraints
Σ_Ω
External Supernova Observations
Σ_sn
Calibration Program Constraints
Σ_cal
Mission Plan

Different cosmologies cannot be distinguished solely with low-z data in the presence of 0.02 mag of photometric zeropoint variation:

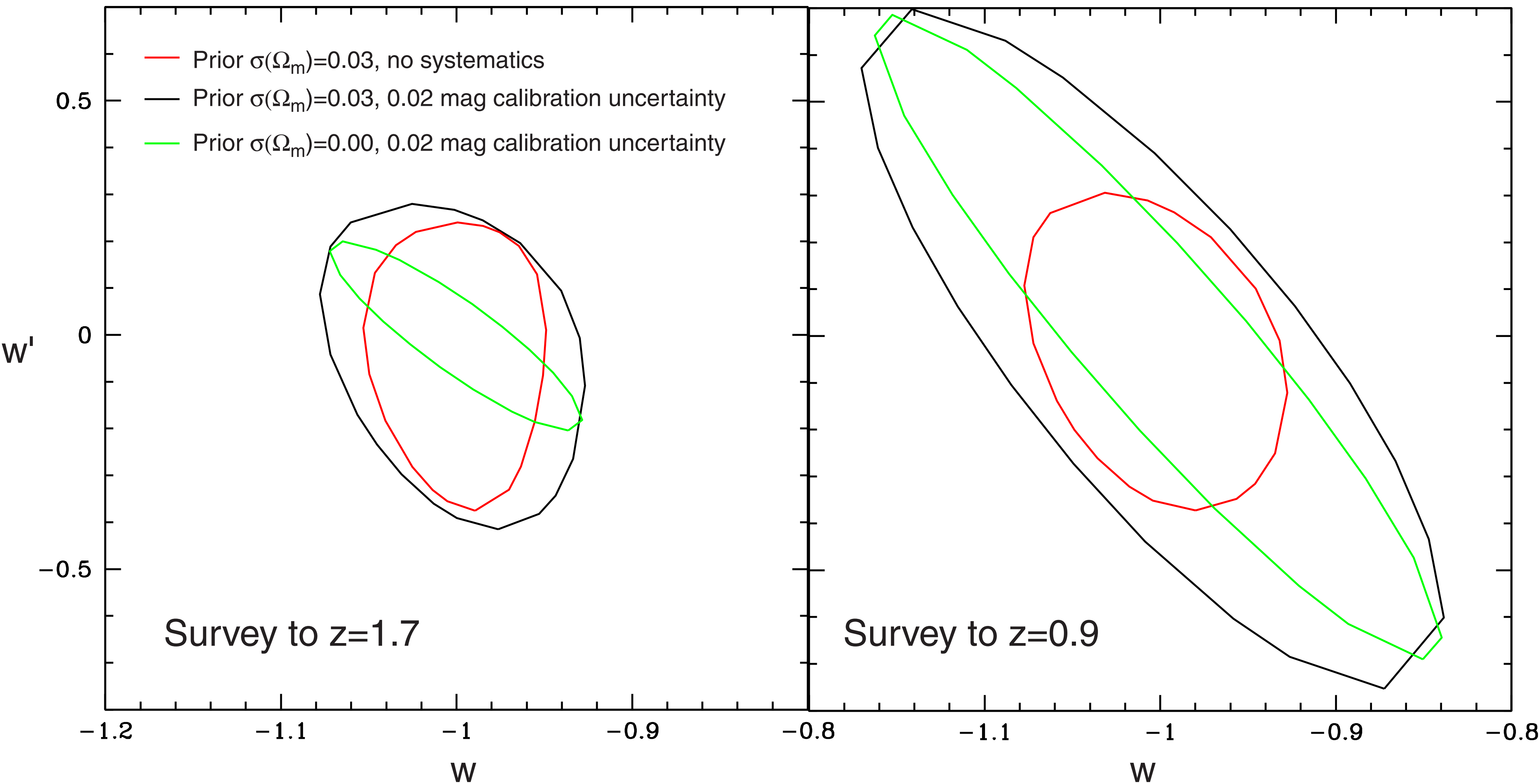


(E. V. Linder & D. Huterer)

How the uncertainty improves as we extend the redshift range.



Effect of Limiting Redshift for Fixed Number of SNe

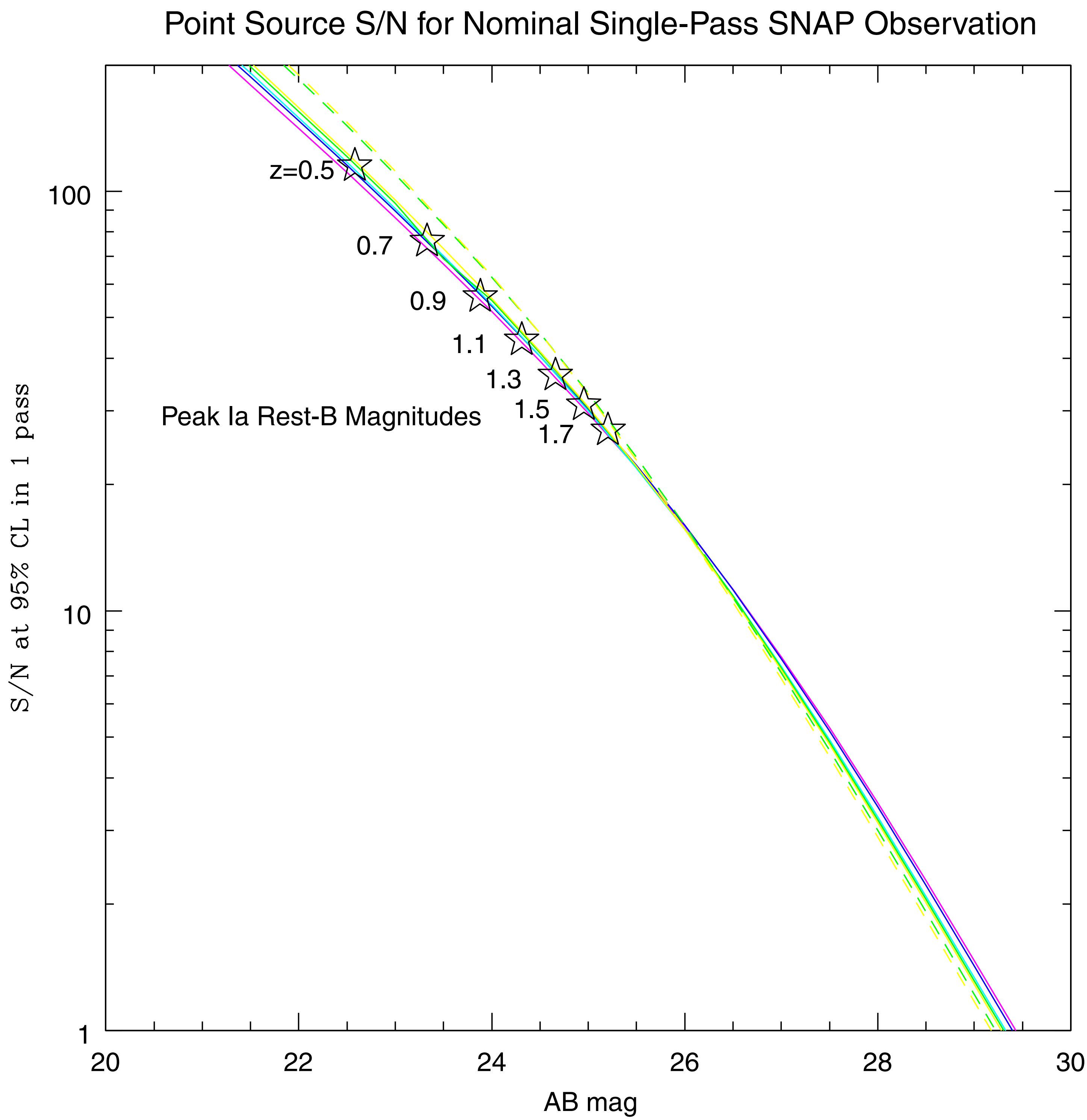


(E. Linder)

Photometric Accuracy from Instrument and Mission Specifications:

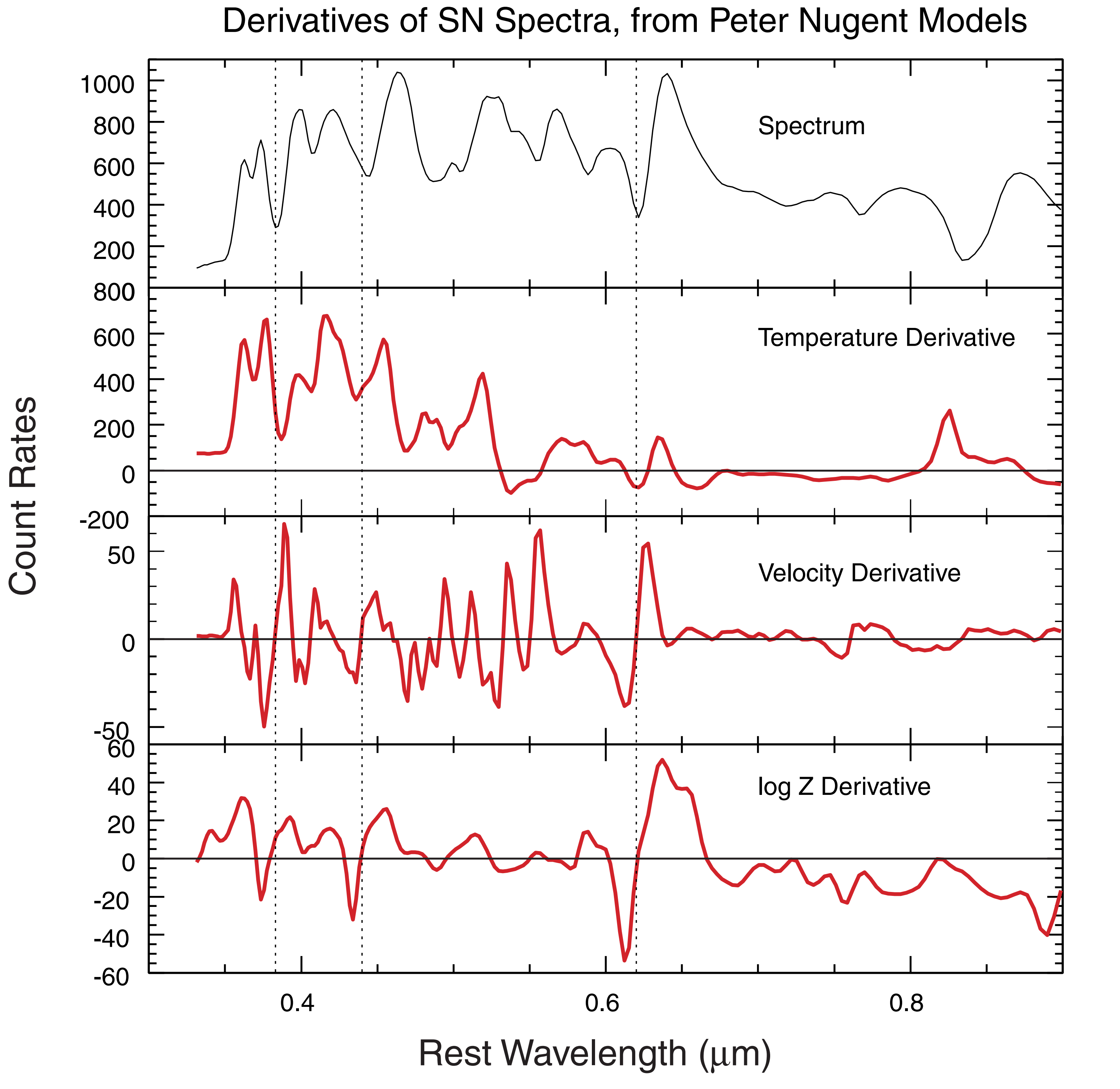
- Point-source photometry is a common astronomical problem.
- Estimate of S/N for given scenario must account for:
    - Diffraction and aberrations
    - Charge Diffusion
    - Pixel response function
    - Undersampling
    - Dithering
    - Host galaxy subtraction
    - Atmospheric Seeing & Extinction (ground only)
    - Poisson noise from source
    - Zodiacal Background
    - Dark Current
    - Read Noise
    - Flatfield Errors
    - Readout and pointing overheads.
    - Cosmic Rays

Those in red are not included in most exposure-time calculators. We have developed a methodology to incorporate ALL of these effects into an estimate of optimal point source extraction accuracy.


Point Source S/N for Nominal Single-Pass SNAP Observation
z=0.5
0.7
0.9
1.1
1.3
1.5
1.7
Peak Ia Rest-B Magnitudes
100
10
1
20
22
24
26
28
30
AB mag
S/N at 95% CL in 1 pass

Spectroscopic Accuracy from Instrument and Mission Specifications:

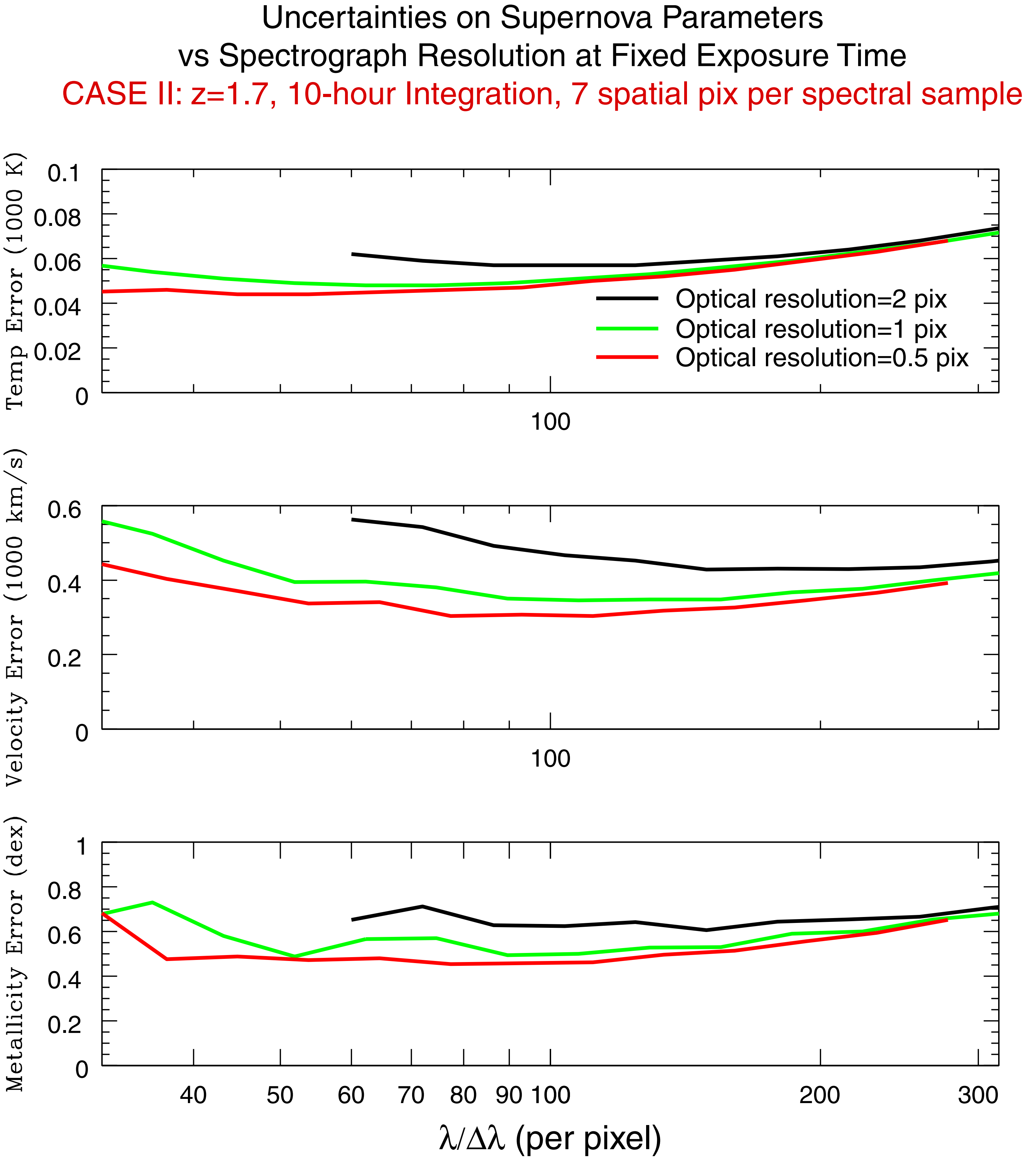
- Photometric S/N programs also give S/N per spectral sample because image slicer produces a series of narrow-band images. Hence S/N estimates given resolution and sampling are well understood.
- Purpose of spectroscopy is to measure features too narrow for filter bands. These features are indicative of intrinsic properties of the supernova.
- Given S/N per resolution element and derivatives of spectrum w.r.t. SN physical properties, Fisher matrices give uncertainties on these parameters. Most difficult to measure: metallicity (log Z).

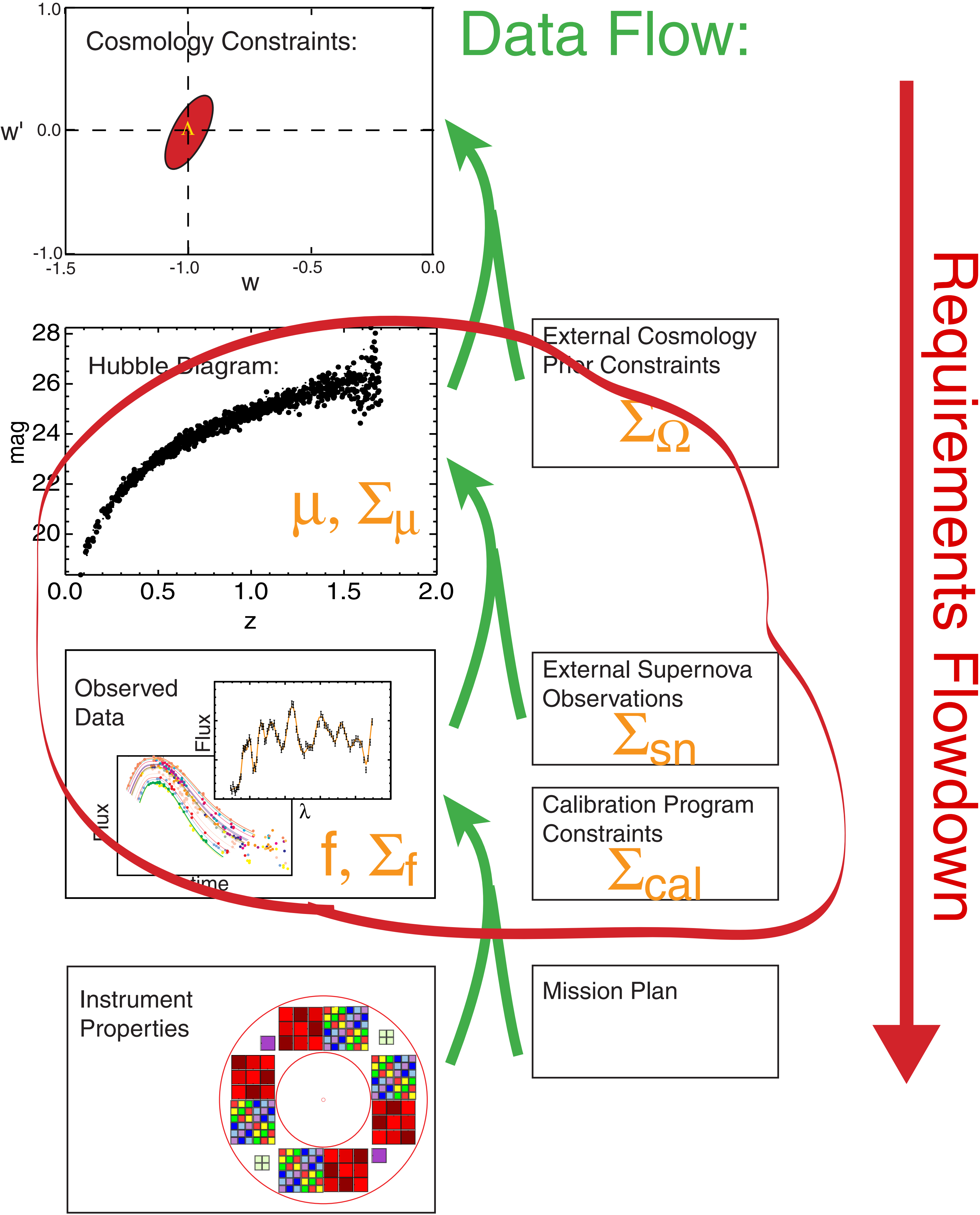


Derivatives of SN Spectra, from Peter Nugent Models
Spectrum
Temperature Derivative
Velocity Derivative
log Z Derivative
Count Rates
Rest Wavelength (μm)
0.4
0.6
0.8
1000
800
600
400
200
800
600
400
200
0
-200
50
0
-50
60
40
20
0
-20
-40
-60

Spectroscopic Accuracy from Specifications: Flowdown Results

- Shot noise, zodi background, dark current, and read noise are all important for $z=1.7$ SNe on HgCdTe detectors.
- Substantial gains from *low-resolution* spectrograph ($R\sim100$) with 1 pixel per spectrograph FWHM. No gain from higher resolution, and "critical sampling" (2 pix per FWHM) is substantial degradation of performance.
- Two-channel (CCD + HgCdTe) spectrograph reduces time required to measure metallicity by ~40% or more.
- Time to measure SNe parameters scales as $(1+z)^6$.


Uncertainties on Supernova Parameters
vs Spectrograph Resolution at Fixed Exposure Time
CASE II: z=1.7, 10-hour Integration, 7 spatial pix per spectral sample
Temp Error (1000 K)
0.1
0.08
0.06
0.04
0.02
0
100
Optical resolution=2 pix
Optical resolution=1 pix
Optical resolution=0.5 pix
Velocity Error (1000 km/s)
0.6
0.4
0.2
0
100
Metallicity Error (dex)
1
0.8
0.6
0.4
0.2
0
40
50
60
70
80
90
100
200
300
λ/Δλ (per pixel)



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Instrument Properties
Mission Plan
Requirements Flowdown

Hubble Diagram from Observed Data:

- Conversion of observed fluxes into distances requires a model of the SN events, propagation to us, and instrument calibration errors.
- Simple case:

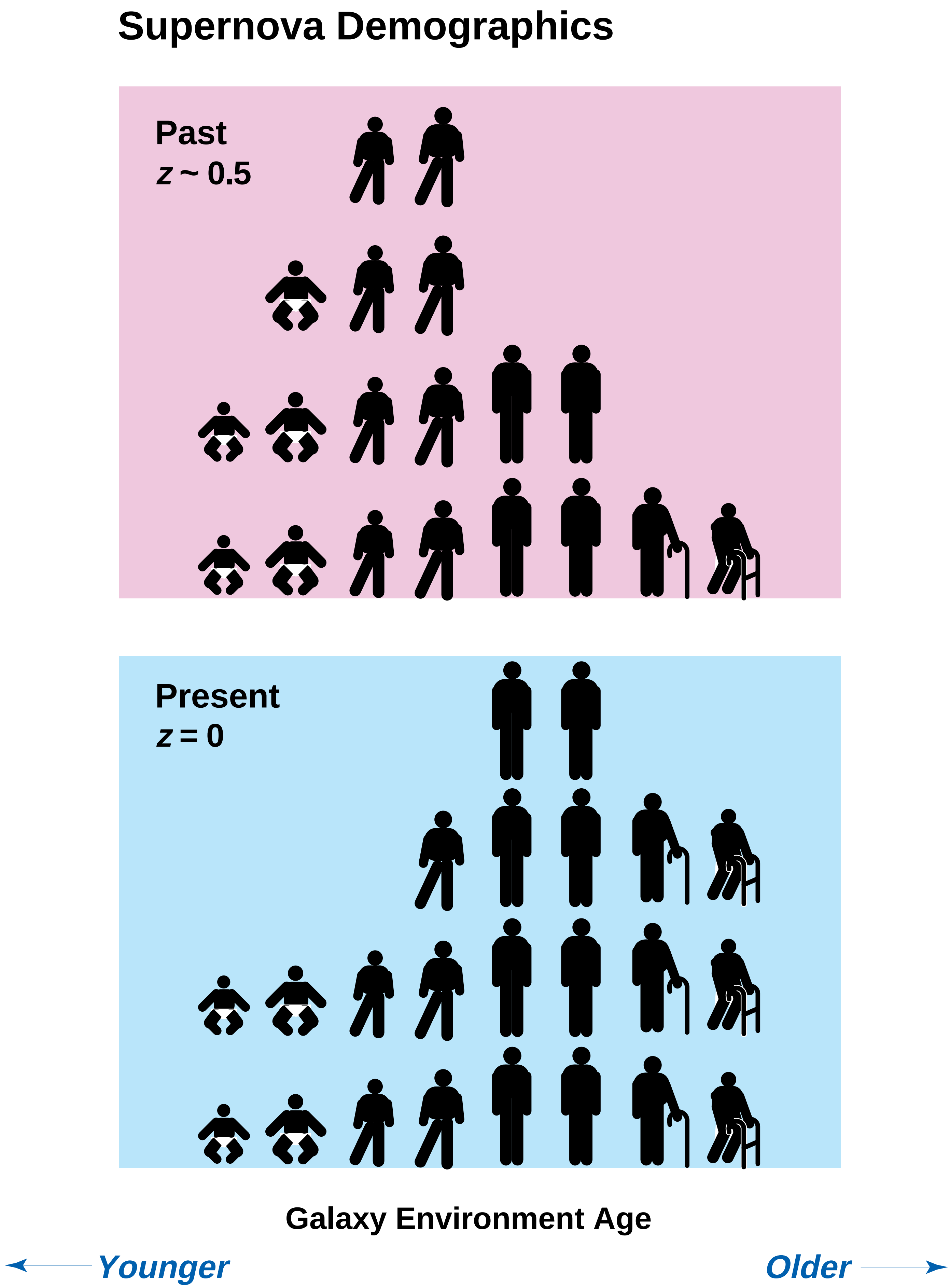
$$m = M + \mu$$

m	is observable
M	is SN model (std candle)
μ	is propagation model

  Fit observations to the model to get best distance.

- More realistic model must include:
    - SN flux/spectrum that depends upon several physical parameters, manifested by stretch, metallicity, etc. – but not explicitly on redshift!
    - K corrections to magnitudes
    - Host dust corrections with unknown A_V, R_V
    - Possible intergalactic ("gray") dust
    - Photometric calibration uncertainties
    - Gravitational lensing magnification
    - Malmquist bias

- Previously, each of these effects has been analyzed individually, no “killers” in the lot. But do data have enough information to constrain all simultaneously?
- The SNAP SNe analysis will be fitting a model with ~20,000 free parameters to ~200,000 or more flux observations. Tractable?
- YES – most parameters are “local” to a single event so we have techniques to hugely compress the fitting matrices. Left with best-fit values for each event’s μ plus 10-20 shared “global” parameters (calibration, gray dust).
- Marginalization over global parameters gives Hubble diagram and covariance matrix.
- SN model is refined using SNAP data itself in a way that does not bias Hubble diagram:
    - Comparing similar SNe at different z to get cosmology
    - Comparing dissimilar SNe at same z to refine SN model.
    - Max-likelihood technique does both simultaneously.


Supernova Demographics
Past
z ~ 0.5
Present
z = 0
Galaxy Environment Age
Younger
Older

1

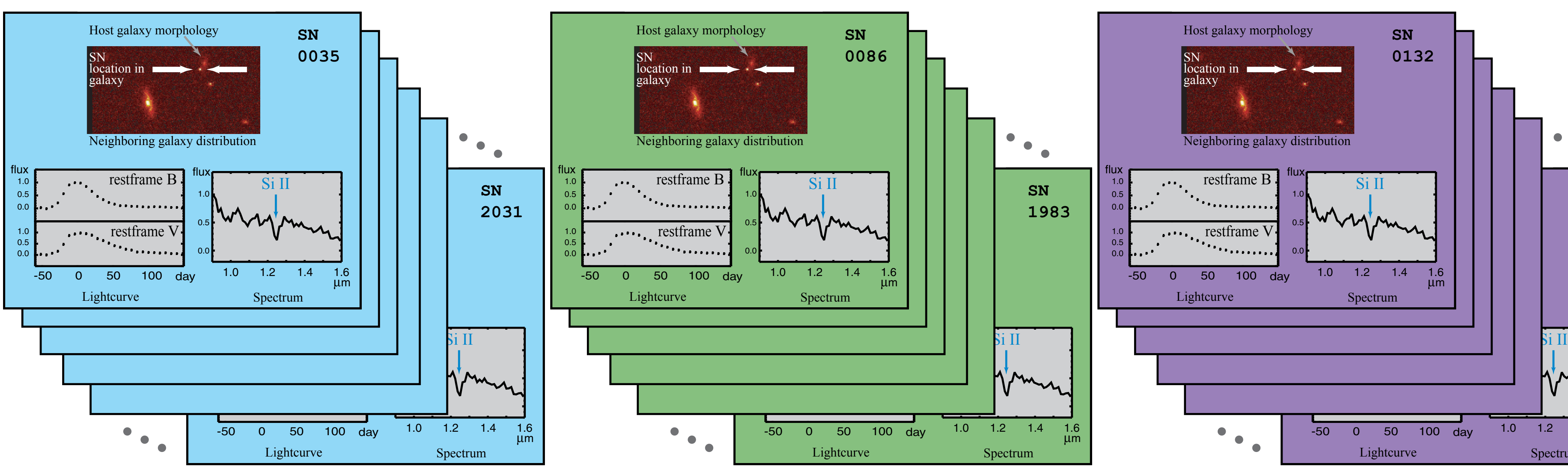
Sort into Like Subsets

Group A:
* Si II in spectrum: type Ia
* elliptical host
* bright UV: low metallicity
* fast rise time: low Ni56 mass
* spectral feature velocities
9000 < v < 10000 km/s

Group B:
* Si II in spectrum: type Ia
* in core of late-type spiral host
* faint UV: high metallicity
* fast rise time: low Ni56 mass
* spectral feature velocities
9000 < v < 10000 km/s

Group C:
* Si II in spectrum: type Ia
* in outskirts of late-type spiral host
* bright UV: low metallicity
* long rise time: high Ni56 mass
* spectral feature velocities
8000 < v < 9500 km/s

Gro
* Si II i
* in core
* brigh
* short
* spectr
8000



2

Each subset gets its own extinction-corrected Hubble diagram:

Group A:
* Si II in spectrum: type Ia
* elliptical host
* bright UV: low metallicity
* fast rise time: low Ni56 mass
* spectral feature velocities 9000 < v < 10000 km/s

⋮

Group B:
* Si II in spectrum: type Ia
* in core of late-type spiral host
* faint UV: high metallicity
* fast rise time: low Ni56 mass
* spectral feature velocities 9000 < v < 10000 km/s

⋮

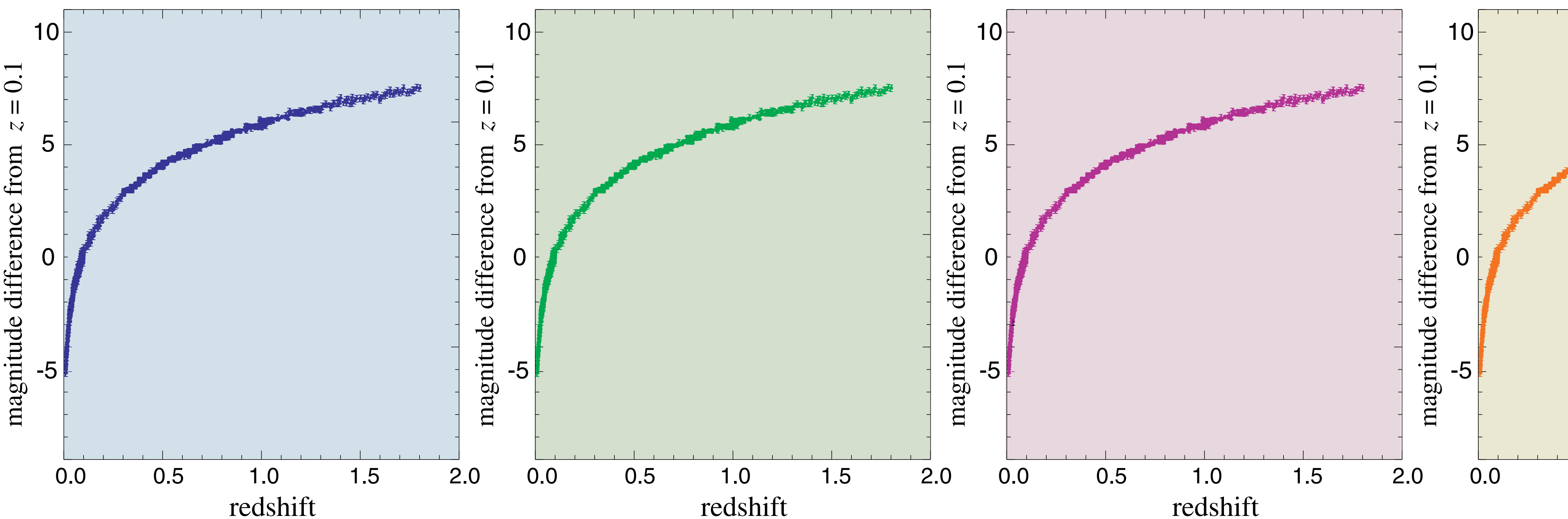
Group C:
* Si II in spectrum: type Ia
* in outskirts of late-type spiral host
* bright UV: low metallicity
* long rise time: high Ni56 mass
* spectral feature velocities 8000 < v < 9500 km/s

⋮

• • •

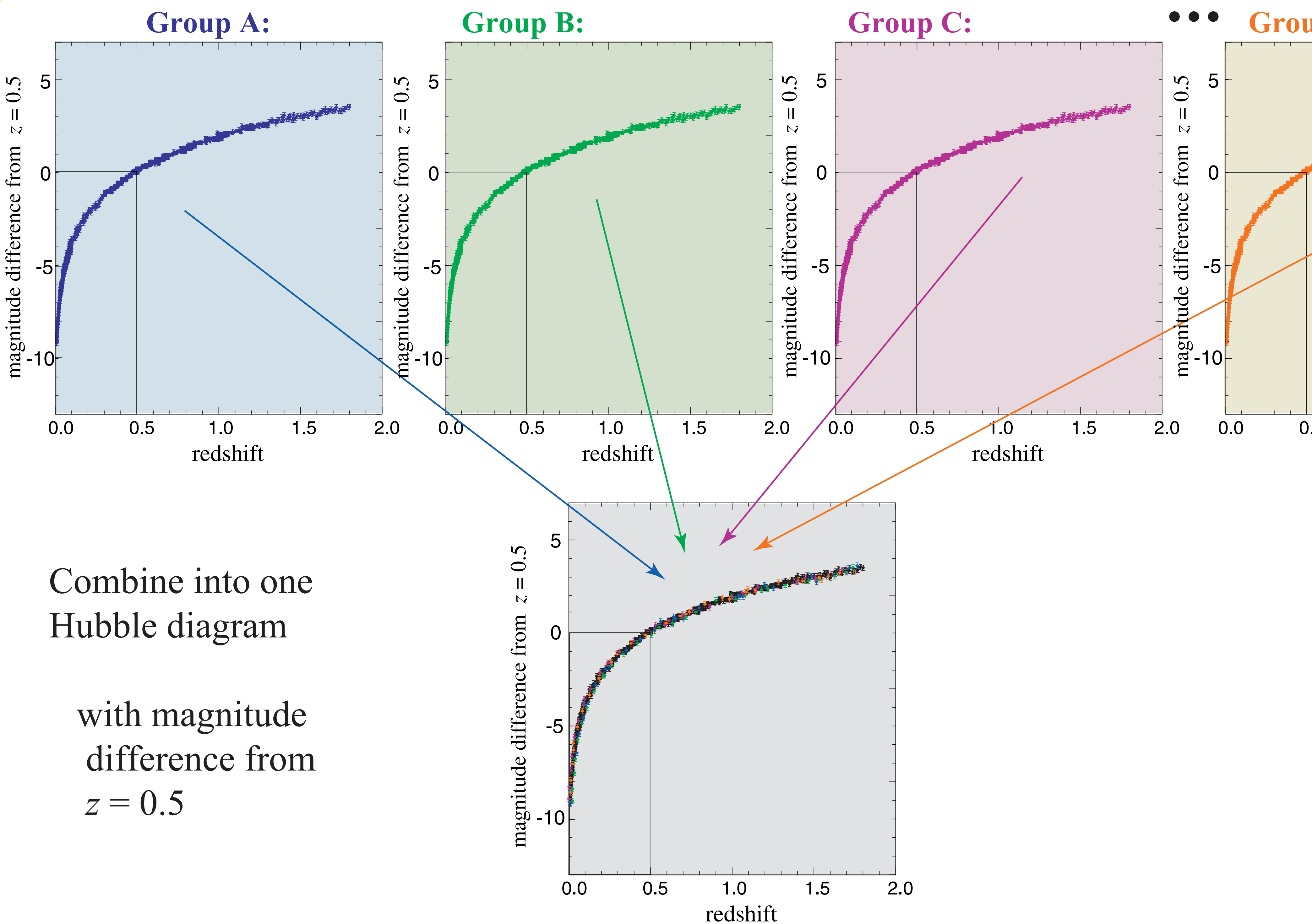
Gro
* Si II i
* in core
* brigh
* short
* spectr

8000



2

Each subset gets its own extinction-corrected Hubble diagram:



Combine into one Hubble diagram

with magnitude difference from $z = 0.5$

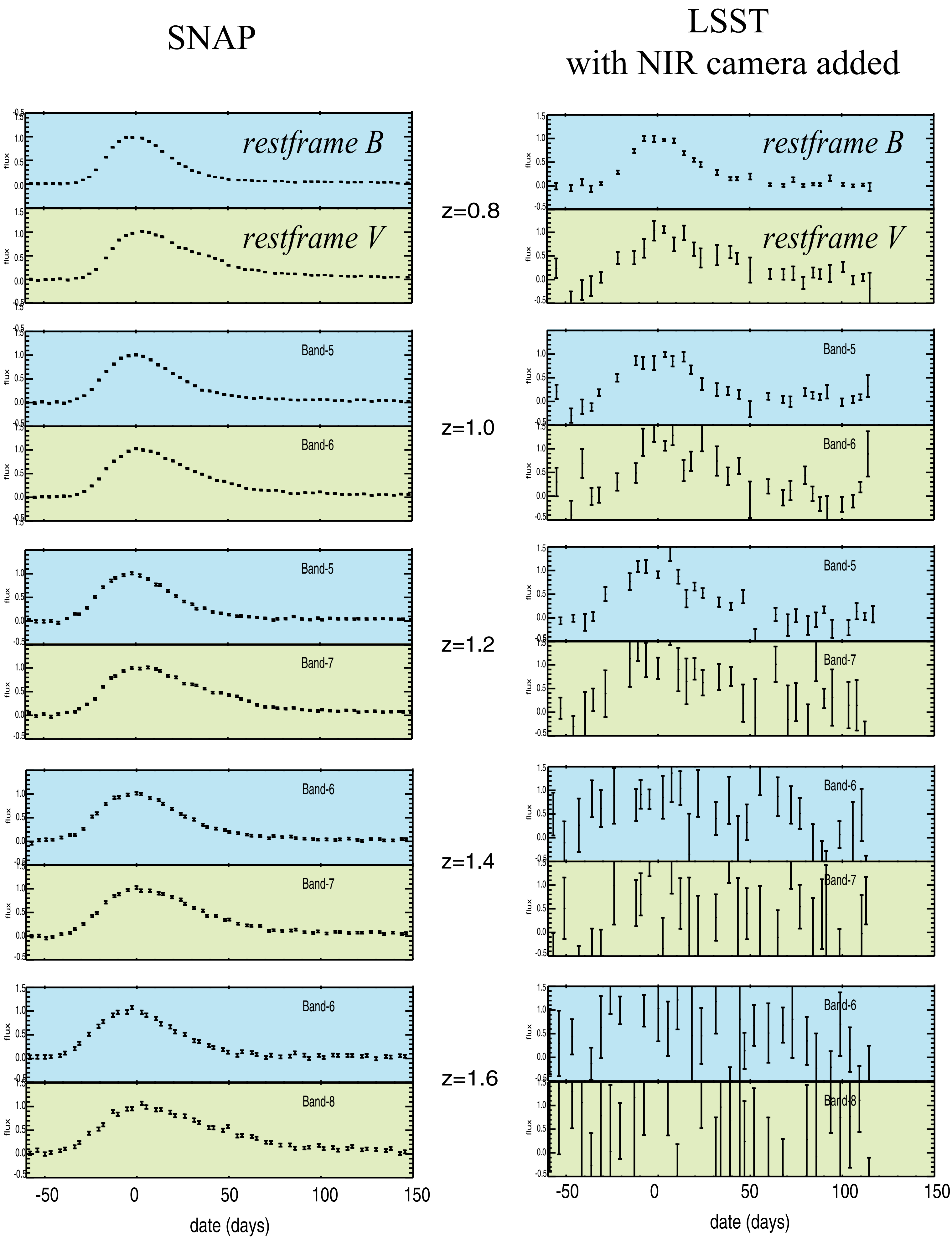
Results of the End-to-End Simulation:

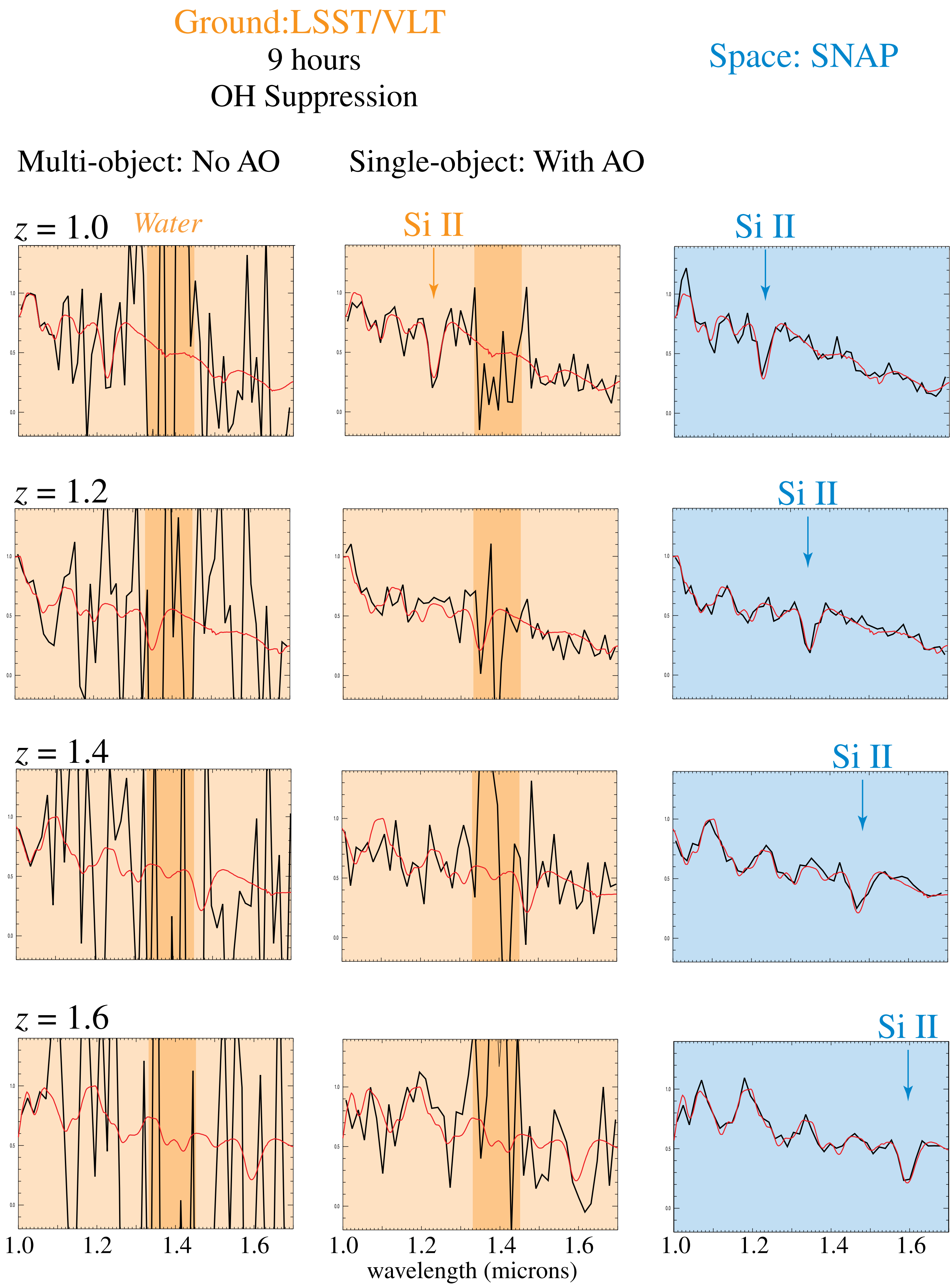
- Nominal SNAP mission analysis in progress – first Hubble diagrams and cosmology constraints now complete.
- Optimization of the SNAP mission plan, especially
  - spectroscopy target redshift distribution,
  - spectroscopic exposure times,
  - sub-sampling of high-z events by host type?
  - is nominal mission duration sufficient for science goal?
  - refinement of calibration requirements.

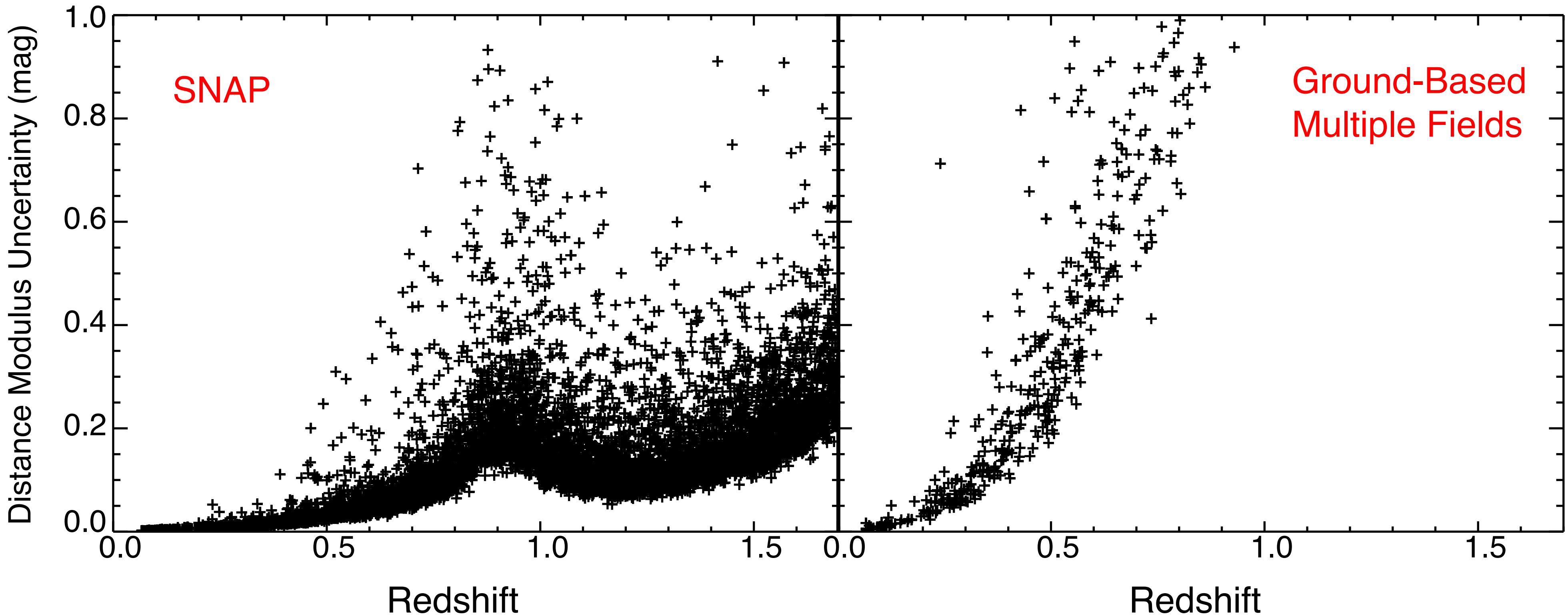
To Be Continued

Results of the End-to-End Simulation: Ground-Based and Other Alternatives

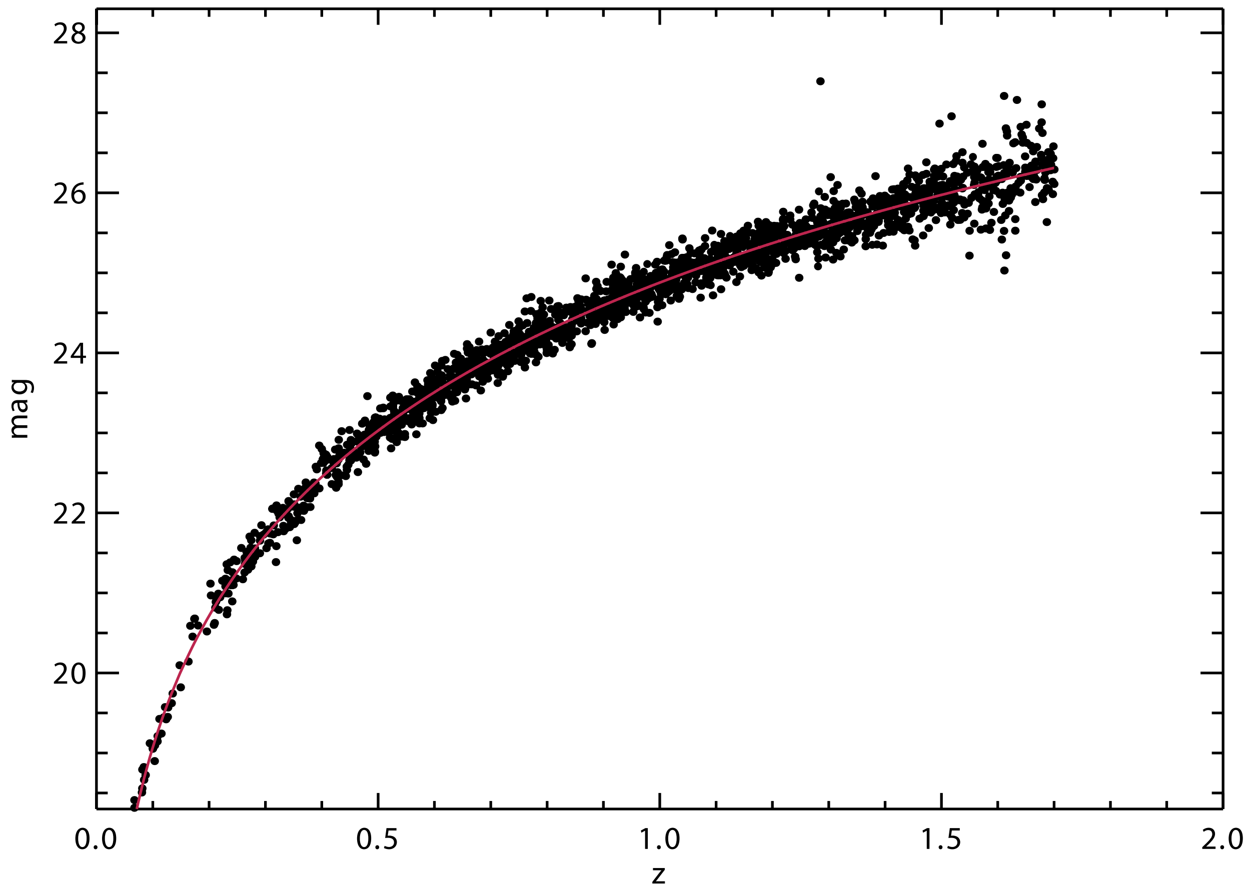
- All SNAP simulation tools are equipped to examine ground-based and space-based alternative sources of data.
- A best-case alternative for 2010:
  - Event detection with LSST (6.5 m, 7 deg^2) to 0.9 micron wavelength, natural seeing (POI-type alternative?)
  - Followup NIR photometry with OH-suppressed 10-meter telescope, tip-tilt correction.
  - Followup NIR spectroscopy with OH-suppressed laser-guided AO 10-meter telescope.
  - Full time on each telescope, Las Campanas weather and seeing histories.
  - Possible NGST access for NIR followup?
  - see analysis by A. Kim; still difficult to obtain sufficient photometry beyond $z \sim 0.9$.
  - Ground is attractive for supplementing SNAP at $z<0.8$.
- End-to-end analyses of alternative scenarios continues. What z range is it productive to supplement with ground observations?

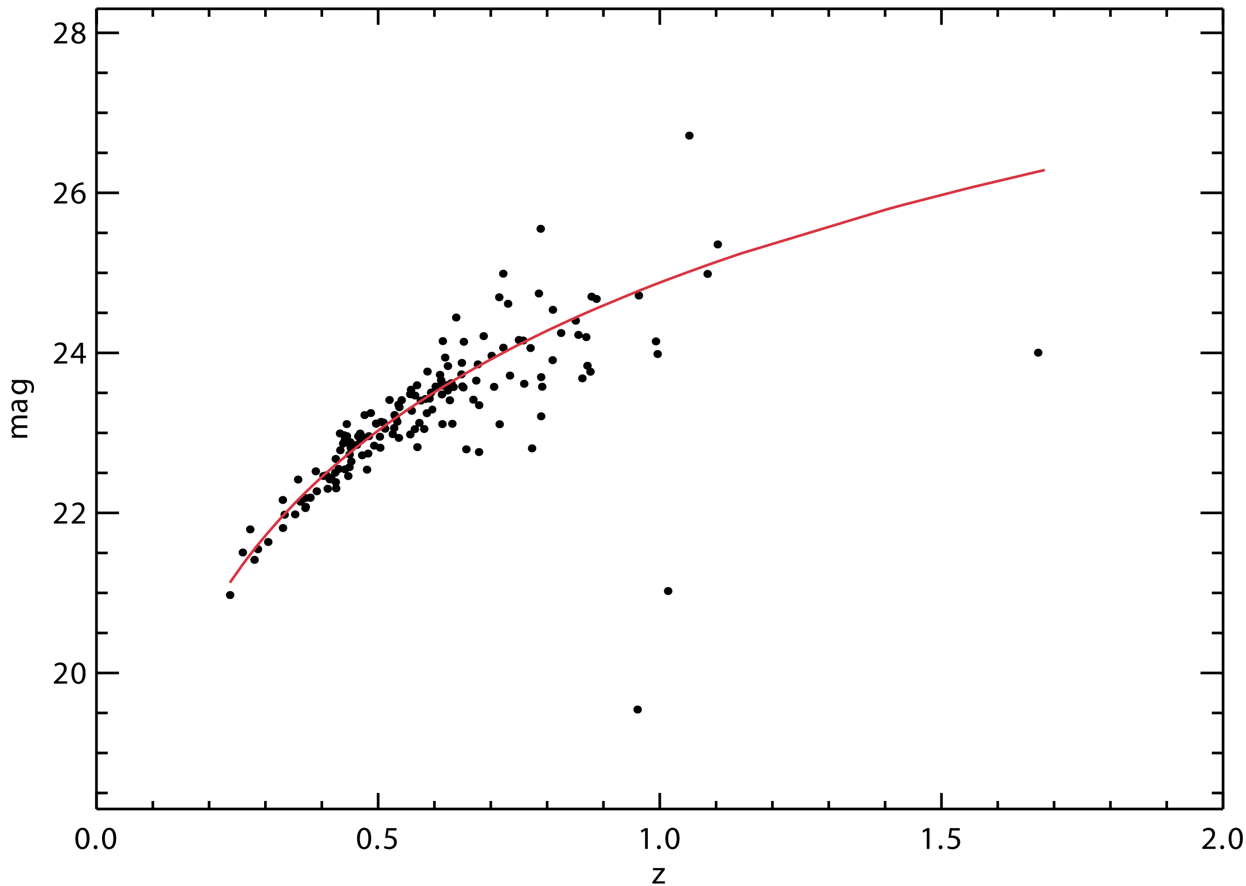

SNAP
LSST
with NIR camera added
restframe B
restframe V
z=0.8
Band-5
Band-6
z=1.0
Band-5
Band-7
z=1.2
Band-6
Band-7
z=1.4
Band-6
Band-8
z=1.6
flux
date (days)
-50
0
50
100
150


Ground:LSST/VLT
9 hours
OH Suppression
Space: SNAP
Multi-object: No AO
Single-object: With AO
z = 1.0
Water
Si II
Si II
z = 1.2
Si II
z = 1.4
Si II
z = 1.6
Si II
1.0
0.5
0.0
1.0
1.2
1.4
1.6
wavelength (microns)



Example calculation: distance uncertainty when simultaneously fitting for SN metallicity and 2-parameter Clayton/Cardelli/Mathis host dust model (see earlier talk by A. Kim for details).


28
26
24
22
20
mag
0.0
0.5
1.0
1.5
2.0
z



28
26
24
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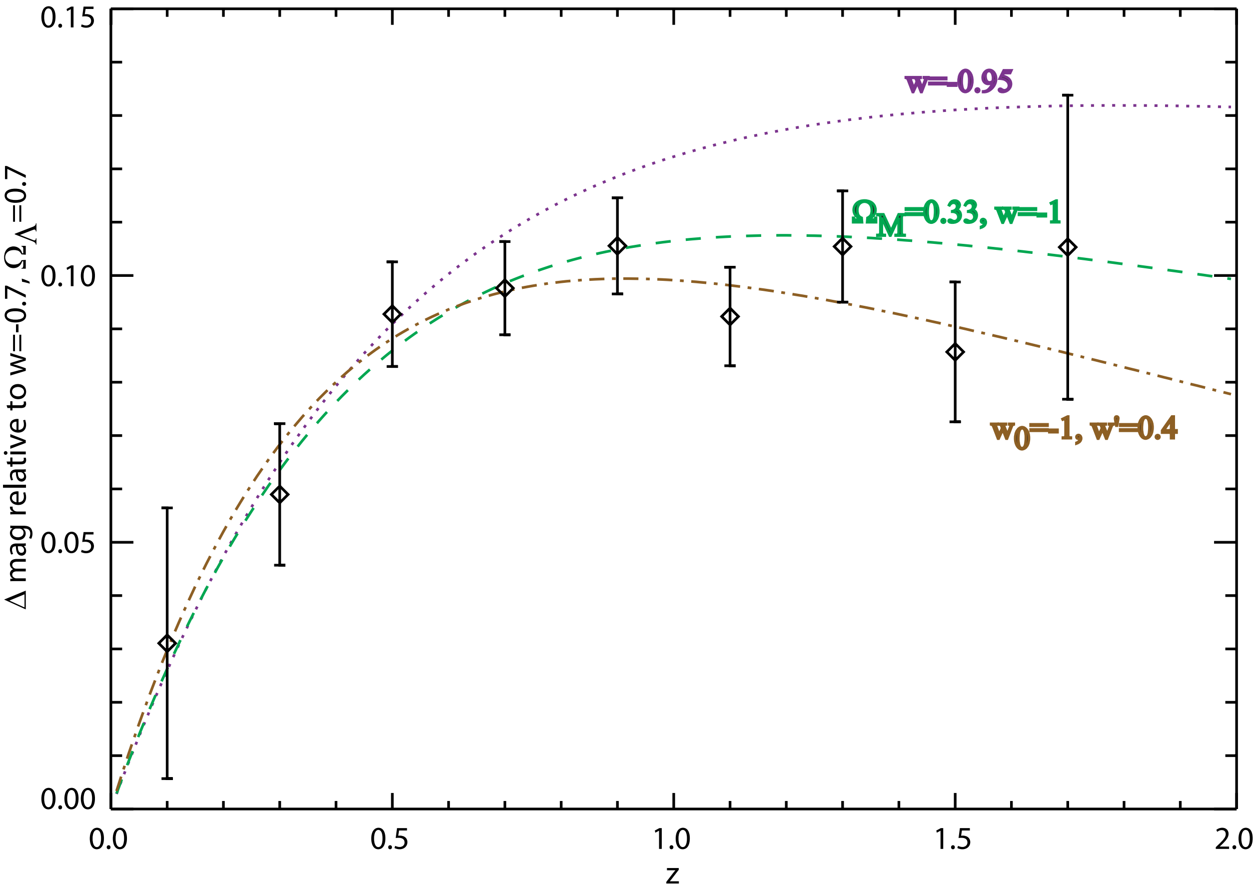
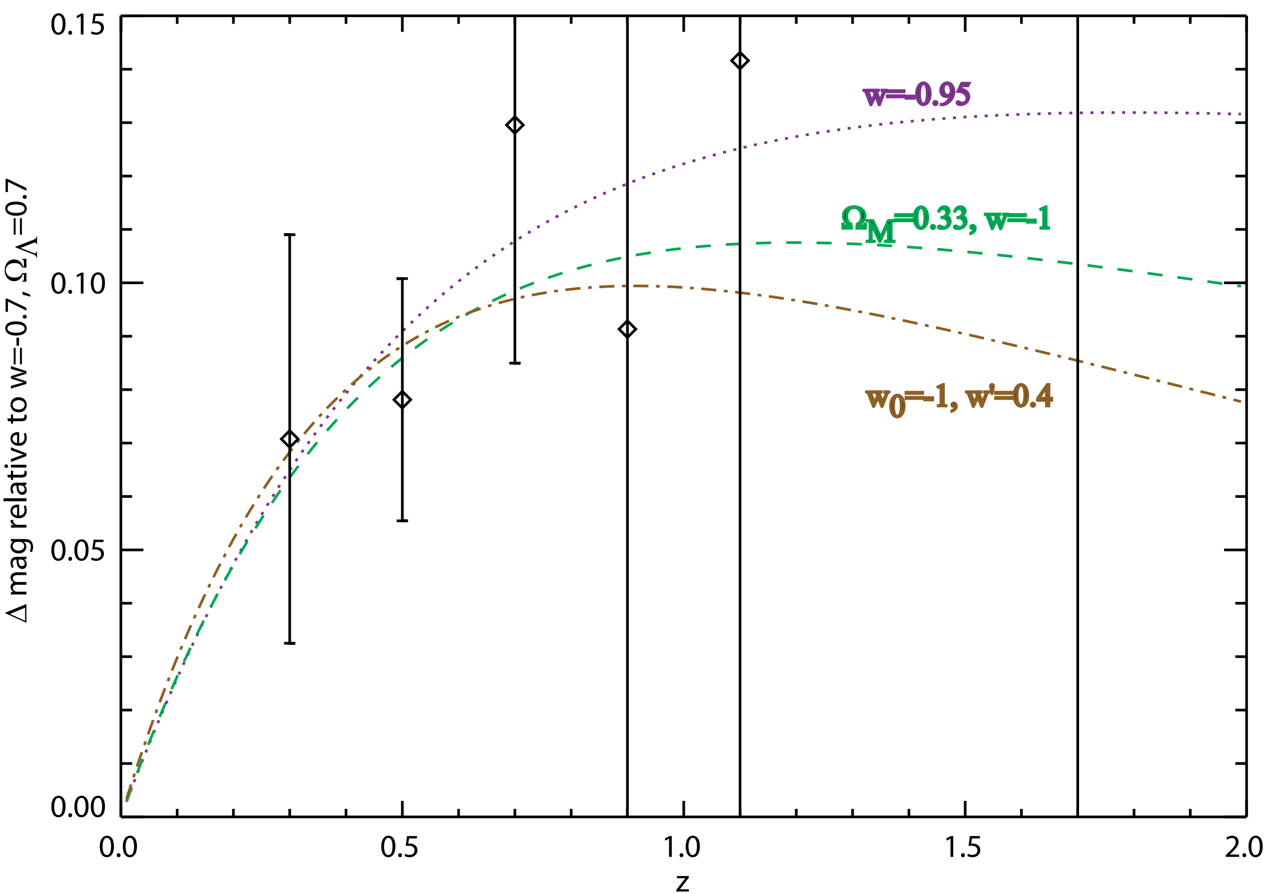
20
mag
0.0
0.5
1.0
1.5
2.0
z



w=-0.95
Ω_M=0.33, w=-1
w_0=-1, w'=0.4
Δ mag relative to w=-0.7, Ω_Λ=0.7
z
0.00
0.05
0.10
0.15
0.0
0.5
1.0
1.5
2.0



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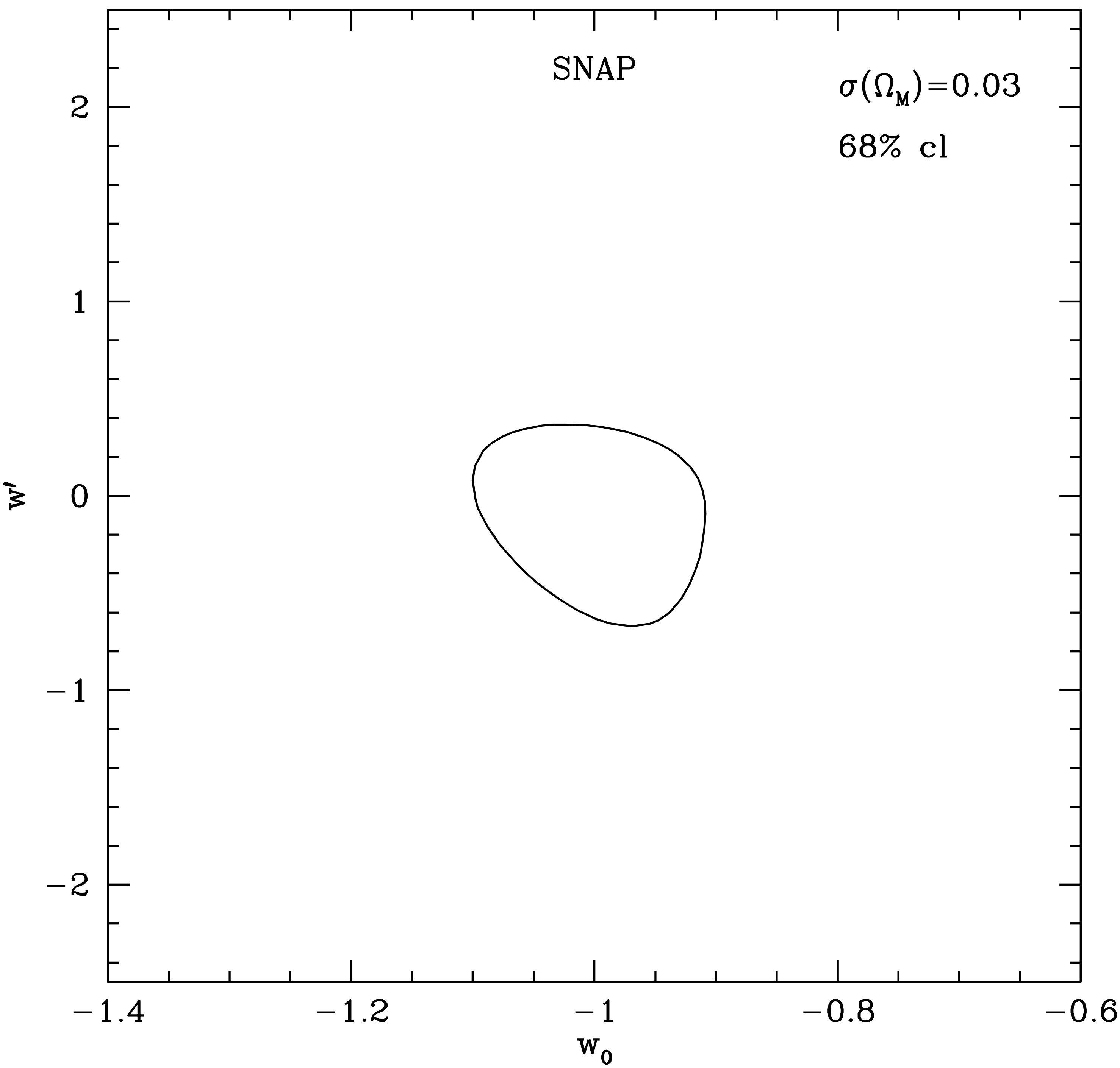
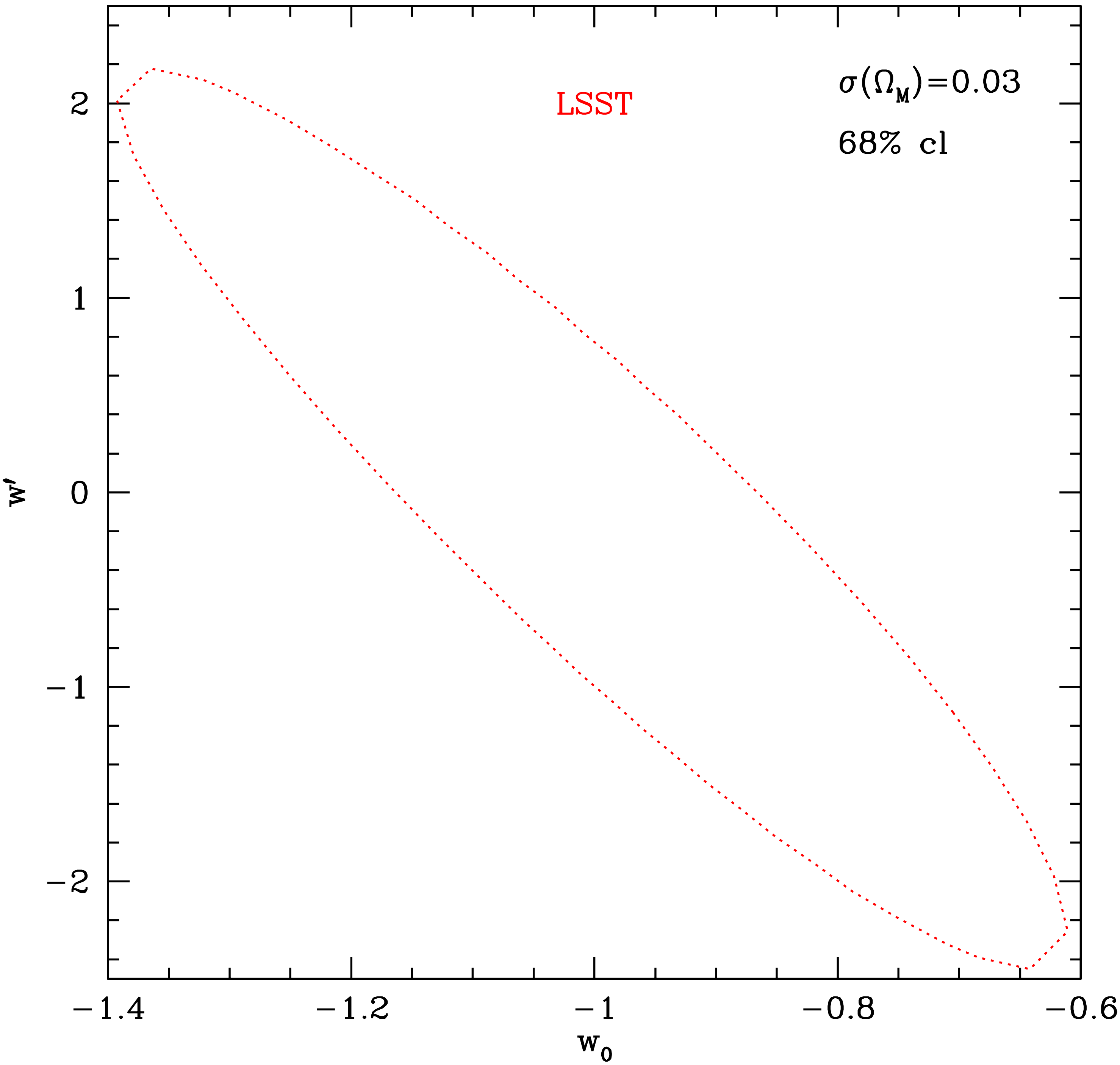
w_0=-1, w'=0.4
0.15
0.10
0.05
0.00
0.0
0.5
1.0
1.5
2.0
z
Δ mag relative to w=-0.7, Ω_Λ=0.7



SNAP
σ(Ω_M)=0.03
68% cl
w'
w_0
2
1
0
−1
−2
−1.4
−1.2
−1
−0.8
−0.6


LSST
$\sigma(\Omega_M)$=0.03
68% cl
w'
w_0
2
1
0
−1
−2
−1.4
−1.2
−1
−0.8
−0.6

SNAPSim: A Generic Survey-Analysis Tool

- Currently integrating all of the previous analysis steps into a unified software structure, including:
  - Orbiting/ground observatory condition simulation, including atmospheric effects
  - Exposure-time & S/N analysis for imaging & spectroscopy
  - Calibration errors
  - Supernova spectrum and light-curve fitting
  - Joint solution for cosmological and systematic variables.
- Under current development:
  - Pixel-level simulations, including shapelet-based Monte-Carlo realization of galaxies (Massey et al).
  - Image-slicer spectrograph optical simulation & extraction methods (CNRS group)
  - More sophisticated models for SN behavior as functions of pre-explosion state.
  - Weak gravitational lensing sensitivity for various cosmological tests ("cosmic shear," cluster counts, non-Gaussian signatures)
- SNAPSim will be useful for analysis of a very wide variety of ground & space-based astronomical surveys.